MEASURING TOTAL CROSS SECTIONS FOR 100-GeV PHOTONS

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ABSTRACT

The total hadronic cross sections for γ rays on various elements, hydrogen through lead, can be measured in a straightforward way at NAL up to photon energies of about 120 GeV. Special counters will be used to detect both the loss of a tagged photon and the appearance of at least one of its reaction products. This is a relatively easy experiment of fundamental theoretical interest and should be considered as one of the first experiments at NAL.

I. INTRODUCTION

The Santa Barbara-SLAC Collaboration[1] recently measured the total photoabsorption cross section to better than 5% in a variety of elements up to 18 BeV. Their experiment appears to have a straightforward extension at NAL with tagged photons up to about 120 GeV being produced from a secondary electron beam.

Electron beam designs for NAL have been discussed by Heusch,[2] Toner,[3] Wilson,[4] and more recently by Diebold and Hand[5] who describe a beam compatible with the 3.5-mrad high flux beam discussed by Barish.[6] Here we review the requirements on the experiment itself and the interest in such a measurement. No great difficulties are forseen and we feel this to be an excellent candidate for performance in an early stage of accelerator operation.

The hydrogen and neutron (from deuterium) cross sections vs proton energy should provide an interesting comparison with πN and KN total cross sections. In the light of possible "problems" with the Pomeranchuk limit of π^+ and π^- cross section uncovered at Serpukhov,[7] it will be extremely interesting to look at $\sigma(\gamma p)$ and $\sigma(\gamma p) - \sigma(\gamma n)$ vs k, the laboratory photon energy.

Since a spin-one object cannot couple to two photons, it was suggested[8] that

Pomeranchuk exchange could not contribute to forward Compton scattering; in Regge language, one expects a wrong-signature nonsense zero in the amplitude. By the optical theorem, this would imply a falloff of the total cross section with energy, contrary to the expectations of the vector dominance model. More recent theoretical work[9] seems to have cured this disease and indicates that, under certain assumptions, the cross section may asymptotically go to a constant. The preliminary results of the Santa Barbara group indicate a small decrease, falling from about 125 μb at 5 GeV to 113 μb at 15 GeV; this 10% loss is similar to that seen for π and K total cross sections. It will thus be of great interest to see whether the γ-ray cross section continues to fall or levels out, as found for π^- and K^- above 30 GeV.[7]

Calculations of the real part of the forward Compton scattering amplitude have been made with finite energy sum rules.[10] Assuming the total cross section to be leveling out, as suggested by the existing data, the sum rules give a $J = 0$ fixed pole in the amplitude, an unpleasant result. The assumptions made in obtaining this unexpected result, namely the high-energy behavior of the total cross section, must be checked experimentally.

The A dependence of the γ-ray total cross section provides information on the vector dominance model.[11] At high energies the model predicts that the cross section should go roughly as that for π's [assuming $\sigma(Vp) \approx \sigma(\pi p)$], i.e., about $A^{0.75}$. At low energies the finite mass of the vector meson is expected to play an important role and the cross sections are expected to go simply as $A^{1.0}$, reflecting the long mean free path for γ rays in the nucleus. The transition between these two dependences is gradual, with typical energy

$$k = M_v^2 \lambda/\hbar c,$$

where λ is the vector meson mean free path in nuclear matter. For the ρ and ω, the transition region should be around 6 GeV. The Santa Barbara group observe an A dependence of $A^{0.9}$ at energies 8 to 16 GeV. This intermediate result can be explained by assuming the light vector mesons (mainly the ρ) to mediate the electromagnetic current only half the time, with heavy vector mesons making up the balance. The transition region for these latter mesons must lie above the 16 GeV measured, but if $M_v < 3$ GeV and $\lambda_V \approx \lambda_\pi$ one would hope to see a change in the A dependence for $k < 100$ GeV. If these heavy vector mesons are composed of many quark-antiquark pairs and thus have smaller mean free paths,[12] the experiment will be sensitive to even higher masses.

II. ELECTRON BEAM

Although we have discussed the beam in some detail previously,[5] the following characteristics are mentioned here since they differ from those of the SLAC beam and have a direct bearing on the experiment.

Duty Cycle

The poor duty cycle at SLAC limited the beam rates for the Santa Barbara experiment. Accidentals (between false tags and the hadron detector) were 10% for their lead points. The duty cycle at NAL will be a factor of 1000 better and such counting-rate problems will be trivial.

Contamination

The e^+ beam used by the Santa Barbara group was a very clean beam. Making an e^- beam from high-energy protons will result in some hadronic (mainly π^-) contamination; we have estimated[5] $\pi^-/e^- < 10^{-3}$ for the beam proposed for NAL. The pions can interact in the tagging radiator, giving a low-energy particle into the tagging counters plus a forward-going hadron which will interact in the target with a cross section ~ 200 times that for γ rays. This is not serious, however, since the probability of a π^- to interact in the lead radiator is only 1/20 of the probability of an electron to give a high-energy γ ray. Further, veto counters can be used to eliminate many of the pion interactions in the radiator by requiring only one charged particle out of the radiator; also the rest of the tagging magnet acts as a sweeping magnet and only neutrons and K^0's can reach the target. It thus appears that beam contamination will result in backgrounds of well under 0.1% and will not be a problem. A check of the contamination can be provided by adding a lead-scintillator shower counter to the tagging counters to give information about the particle being used for tagging. Reversing the beam polarity to run e^+ is expected to increase the contamination by a factor of 2 or 3 and would also allow a check of contamination effects.

Beam Size

The 0.3 radiation-length lead converter used early in the beam increases the beam phase space. We assume that appropriate collimation at an intermediate focus will result in an effective beam size of ±0.5 cm at the external proton target, giving a phase space*:

$$\pi \times 0.5 \text{ cm} \times 0.8 \text{ mrad (vertical)}$$

$$\pi \times 0.5 \text{ cm} \times 1.5 \text{ mrad (horizontal)}.$$

*Multiple scattering in the 0.3 r. ℓ. converter increases the apparent spot size to 3 mm (rms) at 100 GeV. The 0.5-cm figure used here is convervative at this energy.

We now assume the Δp slits are opened until the chromatic aberration increases the spot size at the focus to double the value for $\Delta p/p = 0$. A crude estimate indicates this should occur for $\Delta p/p \sim \pm 2\%$. Using "parallel" beam focusing for the final stage, we then expect that at the tagging radiator the beam size will be*:

$$\pm 1.8 \text{ cm} \times \pm 0.4 \text{ mrad (vertical)}$$

$$\pm 3.5 \text{ cm} \times \pm 0.4 \text{ mrad (horizontal).}$$

This is a much larger beam size than used at SLAC (0.5 cm radius) and it does complicate the design of the experiment somewhat.

III. TAGGED PHOTON BEAM

A clean photon beam is vital to the success of the experiment, as shown by previous failures. This simple experiment was attempted at least twice without success, once at CEA and once at Cornell. The chief problems encountered in the early attempts at Cornell came from a halo of soft gamma rays around the beam, some of which were in coincidence with tagged gamma rays. Counters sensitive to low-energy electrons counted both these halo gamma rays and knock-on electrons from Compton scattering the target. This rate (about 0.1% of the tagging rate) completely swamped any rate due to nuclear interactions of the gamma ray, which was $\sim 10^{-4}$ in a typical hydrogen target. The use of a veto counter was excluded by the low tagging efficiency of 92% (i.e., only 92% of the tagging counts were actually accompanied by a high-energy gamma ray). The Santa Barbara group showed that these difficulties can be overcome by using counters insensitive to low-energy electrons and by sufficient care in the beam design. It appears that internal tagging in a synchrotron is at a significant disadvantage in this respect. At SLAC a 99.7% tagging efficiency is achieved by using a veto counter in the tagging magnet to eliminate tridents, pair production, etc.

At NAL beam halo and off-momentum particles will be reduced by careful collimation and scraping of the beam. With the good duty cycle it should be possible to put a veto counter (with a hole for the beam) directly in front of the radiator; this counter should be a lead-scintillator sandwich in order to veto γ rays as well as charged particles in the beam halo. As for the Santa Barbara experiment various

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*The beam can be "parallel" focused ($\Delta p/p = 0$) to give the phase space

$$\pm 1.3 \text{ cm} \times \pm 0.3 \text{ mrad (vertical)}$$

$$\pm 2.5 \text{ cm} \times \pm 0.3 \text{ mrad (horizontal).}$$

We increased each phase space dimension by $\sqrt{2}$ to estimate the effect of $\Delta p/p = 2\%$.

veto counters will be used to reduce false tags resulting from trident or pair production, interactions of the hadronic component of the beam, any remaining halo effect, etc. Figure 1 illustrates the tagging geometry.

The radiator thickness should certainly be kept below $0.02\,X_0$ to avoid tagging inefficiencies from γ rays pair producing in the radiator. Santa Barbara used $2 \times 10^{-3}\,X_0$, but we feel $0.01\,X_0$, within a factor of two, will probably be satisfactory for this measurement.* Reaction rates for high-A production targets are small, and we would like to use the thickest possible converter.

In Fig. 1, the secondary electrons have energies from 10-40 BeV. Two "standard" magnets with 3-inch gaps are used in series with modified coils to permit the secondary electrons to emerge.

Smearing of the resolution due to the necessarily wide radiator is avoided by placing the tagging counters at $2\bar{x}$ cm outside the magnetic field where $\bar{x}$ is the average distance inside the magnet at which the electron beam strikes the converter. With this geometry all electrons of the same momentum, but different points of origin, are focused into the same tagging counter. The distance L to the counter downstream from the radiator is proportional to $\sqrt{p}$ where p is the momentum of the secondary electron; for $\bar{x} << R$, $L = 2\sqrt{2\bar{x}R}\,[1 + 1/8\,(\Delta x/x)^2]$ where R is the radius of curvature and Δx is the deviation of the point of radiation from $\bar{x}$.

For $\bar{x} = 10$ cm ($\bar{x}$ includes a fringe field of about 4 cm, so $\bar{x}$ is 6 cm inside the pole of the magnet) and $\Delta x = \pm 1.7$ cm, the uncertainty in momentum due to the finite spread of the beam is $\pm 0.4\%$. For a radiated electron momentum of 10 GeV (40 GeV), L = 3.6 m (7.2 m) for a 20-kG field. Thus, a counter bank 3.6 m long is required to cover this range; the minimum magnetic field length is also 3.6 m. For bin widths of 2 GeV, 15 counters are required with widths from 35 cm to 18 cm along the beam; the height of the counters would be equal to the height of the electron beam. A check that the tagging particle is really an electron can be made by backing the counters with a few radiation lengths of lead followed by a scintillator to detect the electron showers. This will also eliminate false tags arising from low energy room background in the tagging counters.

From two 10-ft magnets a 36 mrad deflection of a 100-BeV primary beam can be obtained. Hence, we place the target 50 meters downstream from the tagging radiator. The primary beam passes 1.8 meters from the target at this distance and misses the "large angle" counter by 1.3 meter. The 50 meters could be decreased

*The problems with an overly thick converter include: "double-bremsstrahlung" as a cascade process, loss of the gamma ray by conversion in the tagging radiator, production of low-energy knock-on electrons which cause vetoing of the tagged gamma ray, and multiple scattering of the incident or final electrons causing either a relatively wide-angle gamma ray or loss of tagging efficiency respectively.

somewhat by either adding more magnetic field or by carefully dumping the primary beam in a well-shielded beam dump soon after tagging.

IV. DETECTION OF HADRONIC INTERACTIONS

The simple attenuation technique normally used to measure total cross sections cannot be used for γ rays for several reasons, although it was used by the Santa Barbara group to check their results. First, the cross section for electron pair production is about 200 times larger than that for hadronic processes in hydrogen, and becomes worse for the heavier elements. If one does not look at the incoming charge, electrons behave much like γ rays in shower counters and since the pair production angles are negligible, the beam counter ($\check{C}$ in Fig. 2) can easily be made to count both the noninteracting γ rays and the electron pairs. More serious is the tagging inefficiency which together with the low probability for a hadronic interaction forces one to require direct evidence of an interaction in coincidence with the loss of a beam particle.

The Santa Barbara group used two hadron counters, each having four layers of scintillator and 1 inch slabs of lead; either a four-fold coincidence or a very large shower signal was required to identify an interaction. This discriminated strongly against low-energy (< 500 MeV) electrons dribbling off from asymmetric pair production, while giving an efficiency of at least 99% for pions with > 2 GeV. Although NAL has a much better duty cycle, the counters will be at smaller angles and the pulse height bias may need to be increased over that used at SLAC. This should not cause any inefficiency, however, since the incident energy will be higher and the secondaries will have more energy. Two separate hadron counters were used in the SLAC experiment in order to study systematic errors due to the counters covering neither the very forward nor wide-angle regions. With two counters θ_{min} and θ_{max} could be varied independently. They found that to within the 2% statistical accuracy the deuterium cross sections were invariant under changes in solid angle by factors of 2.5 and 3.3 for the outside and inside acceptances, respectively. This insensitivity is due in large part to the fact that less than 1% of the interactions give a true two-body final state at their energies; at NAL energies this becomes < 0.1% and one has a good chance of catching at least one of the many reaction products.

Another systematic effect was studied in the SLAC experiment by varying θ_{min}. Rare asymmetric electron pair production in the target could simulate a hadron event if the forward electron had insufficient energy to give a veto in $\check{C}$ (in the notation of Fig. 2) and the other electron had wide enough angle and enough energy to count in C 3. Such events gave characteristic correlated pulse heights in the two counters and could be separated from hadron events. Reducing θ_{min} increased the number of these electron pair events, allowing a detailed study. The worst case correction (lead at the lowest energy) was $(5 \pm 5)\%$.

The inner diameter of the hadron counters at NAL will need to be at least twice the beam diameter in order that θ_{min} be reasonably well defined. The relatively large NAL electron beam plus the requirement of going down to $\theta_{min} \approx 125$ MeV/100 GeV means that the small-angle counter will need an inner diameter of about 20 cm and must range up to 80 meters from the target. The large-angle counter will be within a few meters of the target where the beam is smaller and it can have an inner diameter of 10 cm; the outer diameter will be about the same as used at SLAC, 1 meter. To avoid particles passing through the inside of the first counter without striking the second, a third counter will be needed for intermediate angles, as shown in Fig. 2.

A total absorption shower counter will be used for the beam counter. This counter will be about 80 meters downstream of the target where the beam has roughly doubled in size to a 6 cm radius. The counter must be several radiation lengths greater than this in diameter and about 20 radiation lengths deep. A lead-scintillator sandwich would probably give an energy resolution of ± 1 or 2%[13] and might well be adequate. If not, a more exotic counter such as a crystal of lead fluoride[14] could be used. As for the hadron counters, this counter will be mounted on a cart which can be rolled along the beam line so that systematic errors can be studied. At 80 meters the half-angle will be ≈ 1.4 mrad (140 MeV/100 GeV).

V. RATES

The number of electrons expected[5] per pulse is shown in Fig. 3 for 10^{13} protons/pulse and a secondary beam of 4 μsr and $\Delta p/p = 4\%$. The rate depends strongly on energy; at 100 GeV, 3×10^6 e/pulse are expected. To obtain the total number of events from the tagged γ rays we have assumed a 0.01 radiation length radiator and a tagging system capable of tagging photons from $E_e - 40$ GeV to $E_e - 10$ GeV for $E_e \geq 100$ GeV; at lower energies we have taken the limits $0.6\ E_e$ to $0.9\ E_e$. The rates are given for 1/8 radiation length targets of both hydrogen and lead. The hydrogen cross section was taken as 100 μb and the ratio of lead to hydrogen cross sections was assumed to be 120 as measured in the range 8-18 GeV (Ref. 1).

At an electron energy of 100 GeV the rates are quite reasonable, even for lead, 300 events/hour being expected for photon energies from 60 to 90 GeV; for hydrogen this becomes 5000 events/hour. The rates increase rapidly at lower energies, being 10 times higher at an electron energy of 50 GeV. The instantaneous tagging rate at 50 GeV is still an order of magnitude slower than that used at SLAC, so accidentals should not be a problem.

The rates drop off very rapidly as the electron energy increases and the maximum energy obtainable is determined by the actual rates, radiator thickness, and beam time alloted. Taking the rates shown in the figure and a minimum rate of 10 events/hour (i.e., a 5% measurement in two days of running), we can measure the hydrogen total cross section up to $k \approx 130$ GeV ($E_e = 150$ GeV); for lead the limit is $k \approx 110$ GeV. These limits will probably not change a great deal since a factor of three change in the normalization of the curves corresponds to a change of only 10 GeV.

The rates for other reactions can be quickly estimated from Fig. 3. For example $\gamma p \to \rho^o p$ will probably have a cross section of about 10 μb; allowing a factor of ten for detection efficiency gives a counting rate of 50/hour for $E_e = 100$ GeV. The cross sections for $\gamma p \to \omega p$ and $\gamma p \to \phi p$ will probably be down by factors of about 10 and 30, respectively from that for ρ^o's. Nondiffractive cross sections will be much too low to do anything with individual channels. For example, $\sigma(\gamma p \to \pi^+ n) \approx 20\,\mu b/k^2 = 20/40^2 = 0.01\,\mu b$ at 40 GeV, giving only a few events per hour (over all angles) even at this relatively low energy.

An obvious second stage experiment would be to detect recoil protons with a total absorption counter and determine the nature of the missing mass spectrum produced in the high-energy limit. This would shed light on the possible existence of other diffractively produced states besides the ρ, ϕ, ω.

VI. CONCLUSIONS

The measurement of γ-ray total cross sections at NAL can be carried out with a straightforward extension of the technique used in a recent, highly successful experiment at SLAC. The experiment is limited by counting rates to photon energies < 130 GeV for hydrogen and < 110 GeV for lead.

The experiment at NAL will be easier than it was at SLAC because of (a) the better duty cycle (by a factor of 10^3) and (b) the higher energies (allowing cleaner separation of γ's and e's from π's, protons, etc.). The experiment is made somewhat more difficult by the larger phase space of the NAL beam, but this should not affect the experiment in any fundamental way. Contamination (mainly π^-) of the electron beam is expected to be small and its effects easily controlled. Being a pure counter experiment the results should be easily and quickly analyzed.

The relative simplicity of the experiment and the great theoretical interest in the energy and A dependence of the total cross section make this a prime candidate for early running at NAL.

REFERENCES

[1]D. Caldwell, V. Elings, W. Hesse, R. Morrison, F. Murphy, and D. Yount, Total Photoabsorption Cross Sections up to 18 GeV and the Nature of Photon Interactions, International Conference on High Energy Electron and Photon Interactions, Liverpool, England, 1969. (Preliminary results were reported at the Washington meeting, Spring, 1969.

[2]C. A. Heusch, Lawrence Radiation Laboratory UCRL-16830, Vol. III, p. 156; An Electron-Photon Facility for the National Accelerator Laboratory, National Accelerator Laboratory 1968 Summer Study Report B. 9-68-109, Vol. II, p. 163.

[3]W. T. Toner, Electron and Photon Beams at NAL, National Accelerator Laboratory 1968 Summer Study Report B. 9-68-31, Vol. II, p. 125.

[4]R. Wilson, Electromagnetic Physics at NAL, National Accelerator Laboratory 1968 Summer Study Report B. 9-68-49, Vol. II, p. 135.

[5]R. Diebold and L. Hand, Electron-Photon Beam at NAL, National Accelerator Laboratory 1969 Summer Study Report SS-49, Vol. I.

[6]B. C. Barish, A 3.5 Mrad High-Intensity Beam, National Accelerator Laboratory 1969 Summer Study Report SS-30, Vol. I.

[7]J. Allaby et al., Measurements of Total Cross Sections for Negative Particles on Protons in the Momentum Range 20 to 65 GeV/c, presented at Lund International Conference on Elementary Particles, 1969.

[8]V. D. Mur, JETP 17, 1458 (1963); 18, 727 (1964).

[9]H. D. I. Abarbanel et al., Phys. Rev. 160, 1329 (1967).

[10]M. J. Creutz, S. D. Drell, and E. A. Paschos, Phys. Rev. 178, 2300 (1969); S. D. Drell, private communication.

[11]S. J. Brodsky and J. Pumplin, SLAC-PUB-554 (1969); K. Gottfried and D. Yennie, Cornell preprint CLNS-51 (1969); M. Nauenberg, Phys. Rev. Letters 22, 556 (1969); B. Margolis and C. L. Tang, Nucl. Phys. B10, 329 (1969)

[12]R. C. Arnold and P. G. O. Freund, Scattering and Production of Excited Hadrons, Argonne National Laboratory preprint, 1969.

[13]C. A. Heusch and C. Y. Prescott, IEEE Trans. Nucl. Sci. NS-12, 213 (1965).

[14]E. B. Dally and R. Hofstadter, Stanford preprint HEPL-550 (1968).

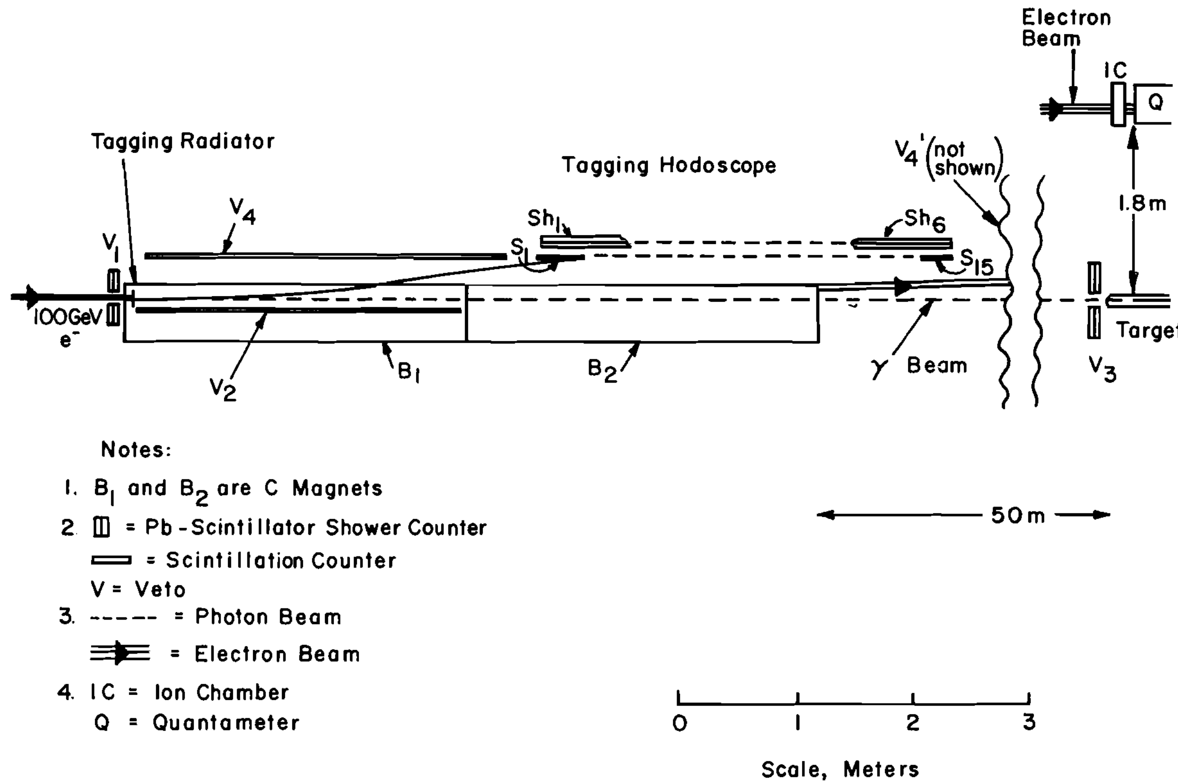

Fig. 1. Photon tagging system, for 60-90 GeV tagged photons.

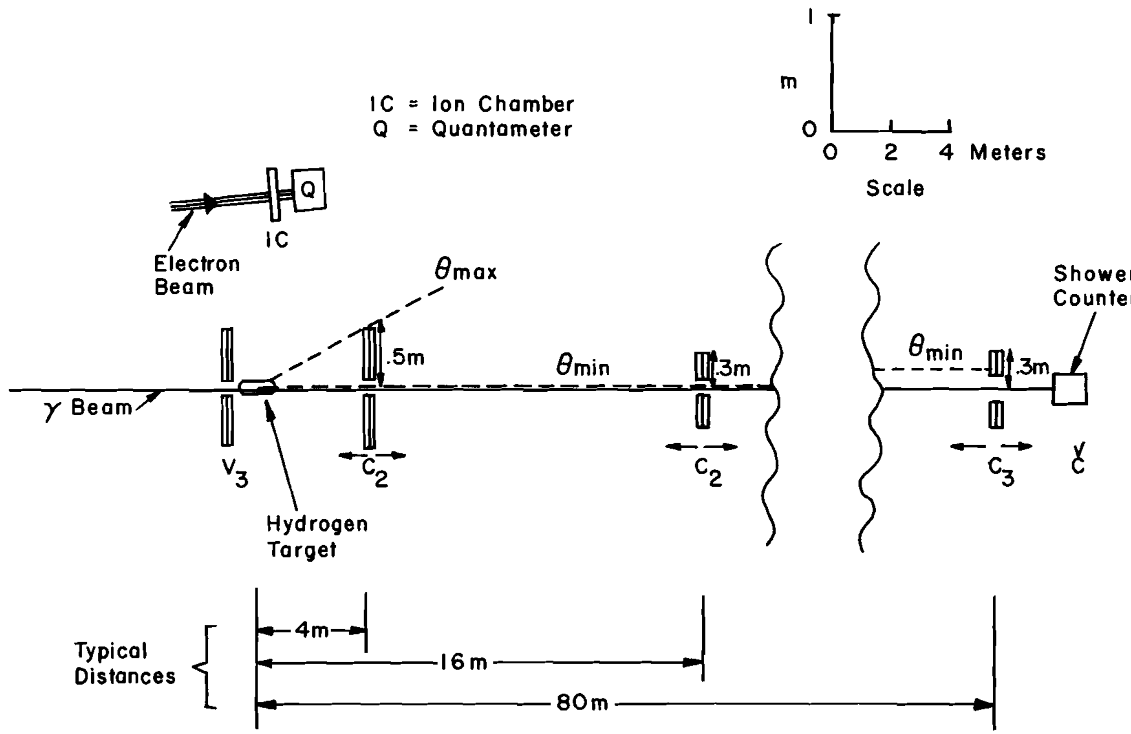

Fig. 2. Hadron detection system.

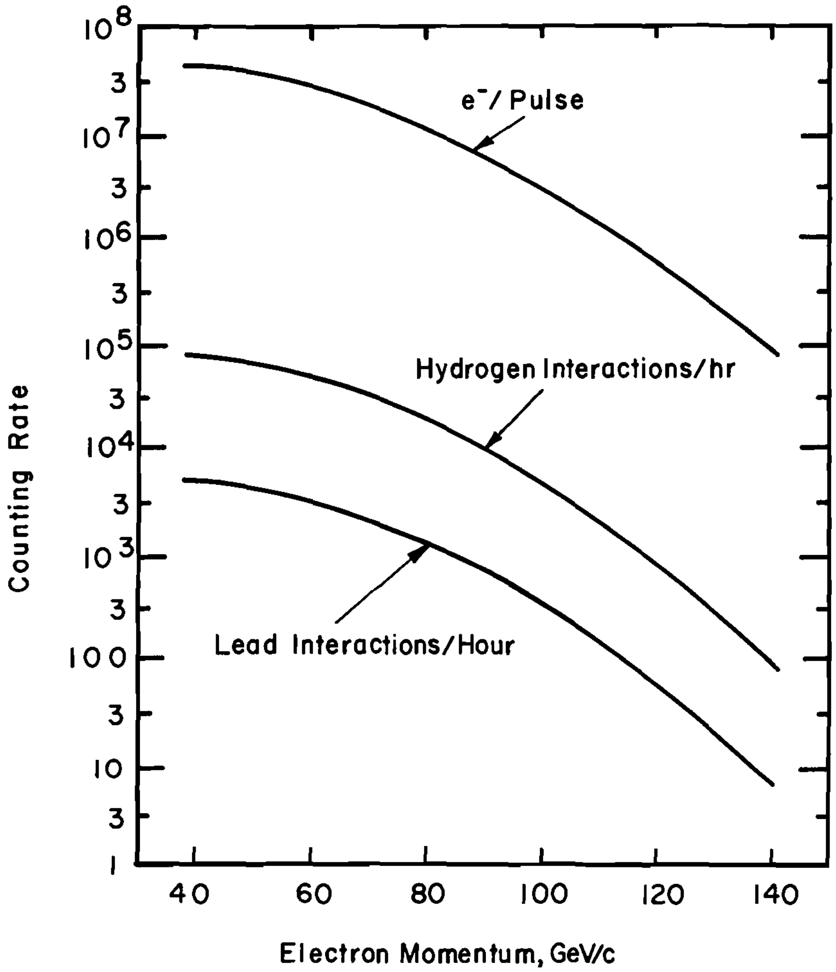

Fig. 3. Reaction rates. The number of electrons per pulse was taken from Ref. 5 for an external proton beam of 10^{13}/pulse and a secondary beam of 4 μsr and $\Delta p/p = 4\%$. The total number of hadronic interactions is shown for a 1-meter liquid hydrogen target and for a 1/8 radiation-length lead target. A 0.01 radiation length radiator was assumed, photon energies from E_e - 40 GeV to E_e - 10 GeV being tagged above 100 GeV; at low energies the range was taken to be 0.6 E_e to 0.9 E_e. Total cross sections used in the calculation: $\sigma_H = 100\,\mu b$; $\sigma_{Pb}/\sigma_H = 120$ as found at 8 to 18 GeV (Ref. 1).